(12) UK Patent Application (19) GB (11) 2 376 584 (13) A

(43) Date of A Publication 18.12.2002

(21) Application No 0114804.8

(22) Date of Filing 15.06.2001

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(51) INT CL^7
H03F 1/32

(52) UK CL (Edition T)
H3W WULPR
H3T T3V T6E T6RD1

(56) Documents Cited
EP 1011192 A2
WO 1999/005869 A2
EP 0731556 A1
WO 1998/012800 A1

(58) Field of Search
UK CL (Edition T) **H3W** WULPR
INT CL^7 **H03F** 1/32
Other:

(54) Abstract Title
An adaptive predistorter using normalised errors

(57) Residual distortion in a cascaded predistorter and amplifier combination 12,10 is measured by comparing the predistorter input S1 with a corresponding signal S2 derived from the amplifier output. In a Cartesian system, both the I and Q errors are normalised. In a polar system, the magnitude only is normalised. The coefficients of the predistorter 12 are updated in dependence on the measured errors. Normalisation of the errors renders the adjustment loop gain independent of the input signal amplitude, yielding predictable convergence. The loop gain may be increased if the amplifier distortion is large and reduced if the distortion is low. The predistorter 12 and its adaptive controller 24 are digital. The predistorter may use look-up tables.

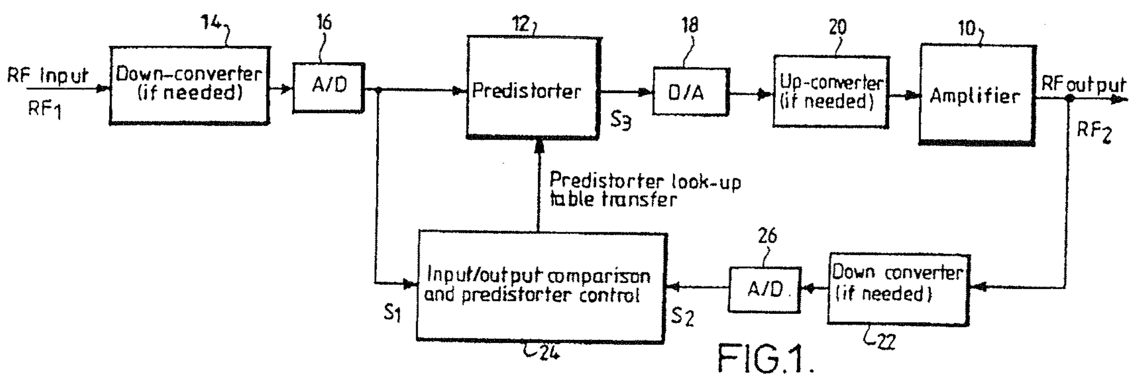
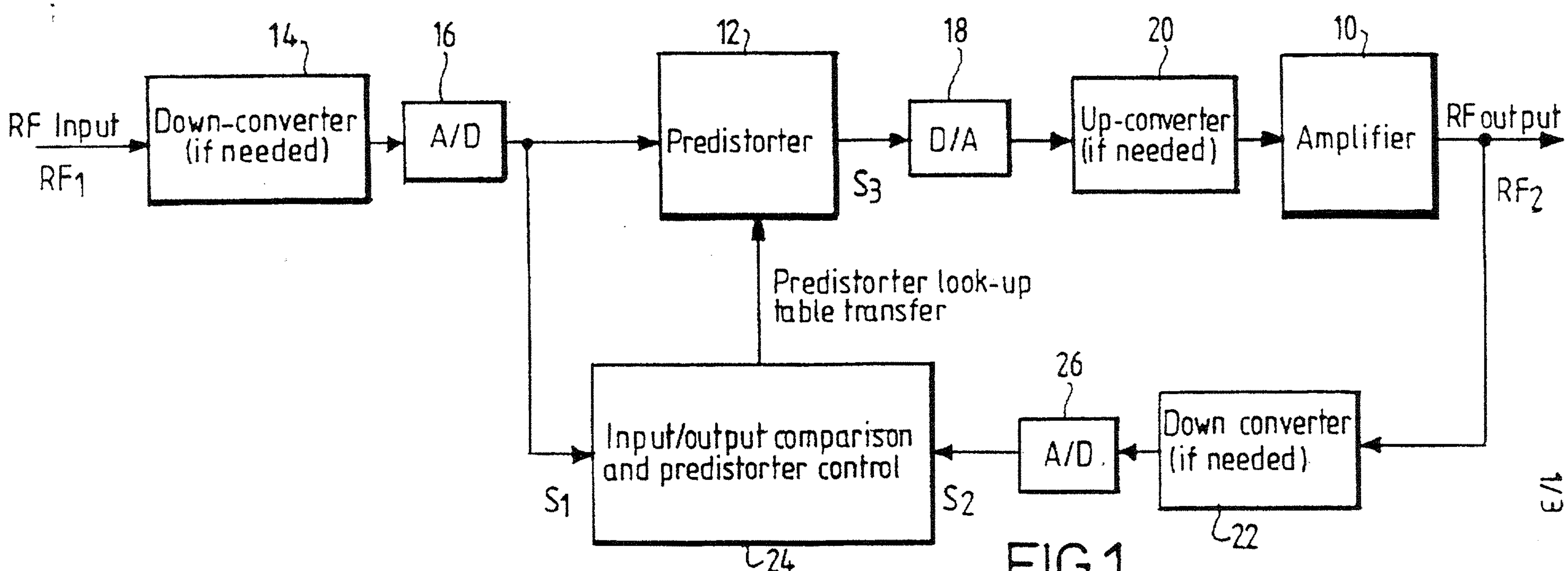


FIG.1.

GB 2 376 584 A

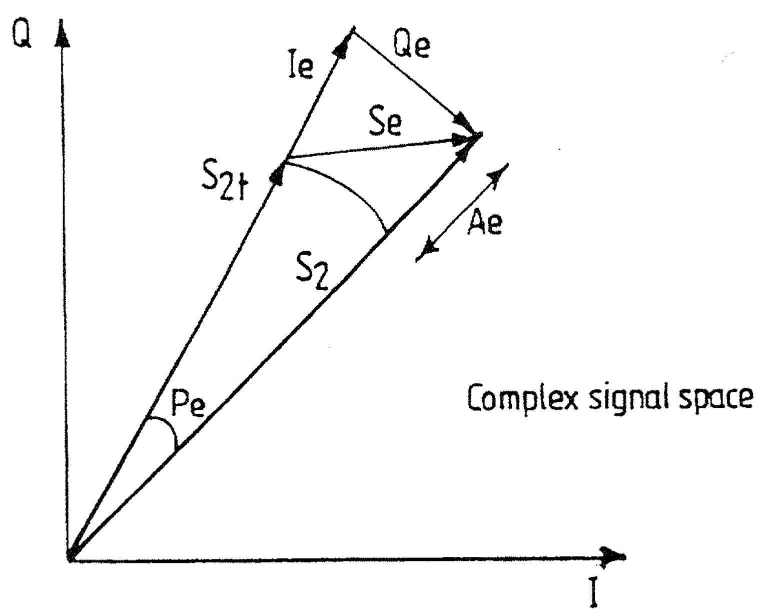
At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

The claims were filed later than the filing date but within the period prescribed by Rule 25(1) of the Patents Rules 1995.



14
16
12
18
20
10
RF Input
RF1
Down-converter (if needed)
A/D
Predistorter
S3
D/A
Up-converter (if needed)
Amplifier
RF output
RF2
Predistorter look-up table transfer
26
Input/output comparison and predistorter control
S1
S2
A/D
Down converter (if needed)
24
22

FIG.1.



Q
Ie
Qe
Se
S2t
Ae
S2
Pe
Complex signal space
I

FIG.2.

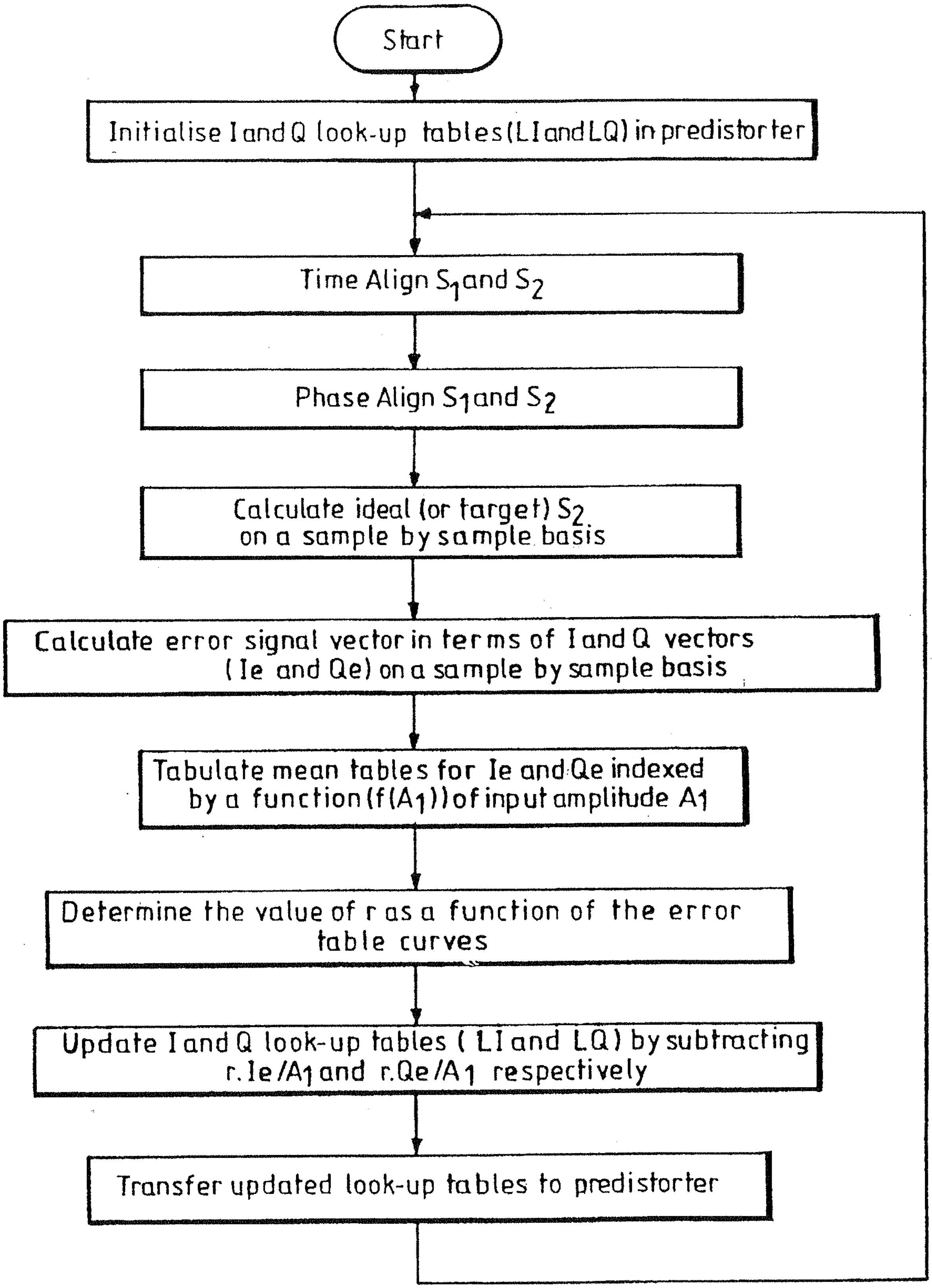

Start
Initialise I and Q look-up tables (LI and LQ) in predistorter
Time Align S_1 and S_2
Phase Align S_1 and S_2
Calculate ideal (or target) S_2 on a sample by sample basis
Calculate error signal vector in terms of I and Q vectors (Ie and Qe) on a sample by sample basis
Tabulate mean tables for Ie and Qe indexed by a function ($f(A_1)$) of input amplitude A_1
Determine the value of r as a function of the error table curves
Update I and Q look-up tables (LI and LQ) by subtracting $r.Ie/A_1$ and $r.Qe/A_1$ respectively
Transfer updated look-up tables to predistorter

FIG. 3.

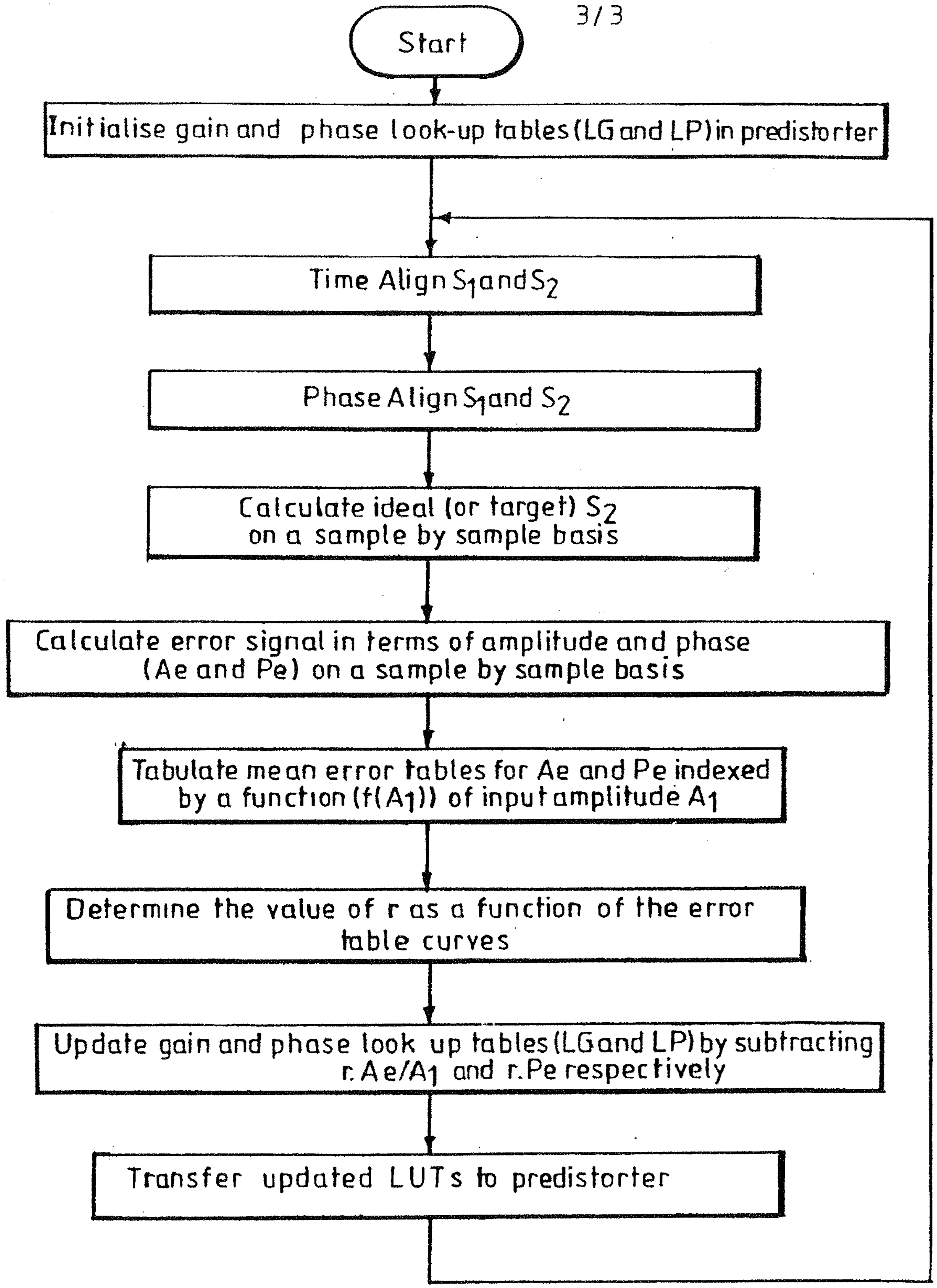

Start
Initialise gain and phase look-up tables (LG and LP) in predistorter
Time Align S1 and S2
Phase Align S1 and S2
Calculate ideal (or target) S2 on a sample by sample basis
Calculate error signal in terms of amplitude and phase (Ae and Pe) on a sample by sample basis
Tabulate mean error tables for Ae and Pe indexed by a function (f(A1)) of input amplitude A1
Determine the value of r as a function of the error table curves
Update gain and phase look up tables (LG and LP) by subtracting r.Ae/A1 and r.Pe respectively
Transfer updated LUTs to predistorter

FIG.4.

2376584

SIGNAL CORRECTION TECHNIQUES

The invention relates to methods of, and apparatus for, controlling distortion counteracting equipment such as a predistorter.

In a case where signal handling equipment distorts a signal upon which it operates, it is known to use a lineariser to reduce distortion in the output signal of the equipment. It is known to perform linearisation adaptively by monitoring errors in the output signal and using information on these errors to adjust the linearisation to reduce the errors as far as possible. Typically, predistorters are used to linearise amplifiers.

One aim of the invention is to provide improvements in the manner in which distortion counteracting equipment, such as a predistorter, is controlled.

According to one aspect, the invention provides apparatus for adapting distortion counteracting equipment, wherein said counteracting equipment employs a group of coefficients to adjust a consequential signal in order to ameliorate distortion in an output signal produced by signal handling equipment in response to an input signal, the apparatus comprising error measuring means for measuring errors in the output signal, modifying means for modifying measured errors to render them less dependent on the input signal's amplitude and correcting means for changing said coefficients by amounts dependent on modified errors.

The invention also consists in a method of adapting a distortion counteracting equipment, wherein said counteracting equipment employs a group of coefficients to adjust a consequential signal in order to ameliorate distortion in an output signal produced by signal handling equipment in response to an input signal, the method comprising measuring errors in the output signal, modifying measured errors to render them less dependent on the input signal's amplitude and changing said coefficients by amounts dependent on modified errors.

In one embodiment, the consequential signal is the input signal to the signal handling equipment and the counteracting equipment is a predistorter.

Thus, the invention improves the ability of distortion counteracting equipment to converge to the best values for the coefficients to optimise the elimination of distortion in the output signal. This is achieved by reducing the dependence of the changes to the coefficients on the input signal amplitude (which can vary greatly, e.g. in the case of CDMA signals), i.e. by reducing the dependence of the coefficients' loop gains on the input signal's amplitude. This means that the coefficients converge equally quickly.

In one embodiment, the coefficients are indexed by a function of the input signal's amplitude such that the input signal's amplitude selects the coefficient or coefficients that are used in the distortion amelioration process at any given time. Preferably, the coefficients are arranged in one or more look-up tables indexed by functions of the input signal's amplitude.

In one embodiment, the measured errors are indexed according to a function of the input signal's amplitude, i.e. the measured errors are tabulated against a function of the input signal's amplitude. For example, measured errors can be obtained for each of a series of values of the function of the input signal's amplitude. Where the coefficients are also indexed against the same function of the input signal's amplitude, it is possible to arrange the adaption process such that a measured error is used in the adaption of the coefficient sharing the same index value.

Where a function, $f(a)$, of the input signal's amplitude, a, is used to index coefficients or errors, the function may be simple, such as $f(a) = k.a$, or more complex, such as $f(a) = k.a^2$ (here, k is an arbitrary constant). In the simplest case, $f(a) = a$.

In one embodiment, errors in a particular parameter are measured and these errors are used to adjust coefficients which act on the same signal parameter.

In one embodiment, the coefficients are segregated into sub-groups, each sub-group for altering a different parameter of the consequential signal. The errors used to adapt coefficients in a sub-group may be errors in the parameter to which the sub-group pertains. For example, where the coefficients fall into amplitude and phase sub-groups, the coefficients in the sub-groups are adapted on the basis of amplitude and phase errors respectively. Where the coefficients fall into sub-groups for orthogonal components, errors in each orthogonal component are used to adapt the coefficients for the respective component.

In one embodiment, the error values are derived over a period of time to reduce the effects of noise on the error values. For example, the error values could be accumulated and averaged over a period of time. The error values may be processed to remove the affects of noise, e.g. by filtering the errors or by fitting them to a curve. Similarly, after adaption, the coefficients may be processed to remove the affects of noise, e.g. by filtering the adapted coefficients or by fitting them to a curve.

Preferably, the modified errors are substantially independent of the input signal's amplitude.

In one embodiment, at least some measured errors are modified by dividing them by the input signal's amplitude to make them substantially independent of the input signal's amplitude. Where a measured error is divided by the input signal's amplitude and the measured errors are indexed by a function of the input signal's amplitude, the measured error can be divided by the amplitude value which indexes that measured error.

In one embodiment, the changes to the coefficients are proportional to modified errors. Preferably, the changes to the coefficients are fractions of the modified errors. Advantageously, the fractions can be changed to optimise the adaption rate of the coefficients. For example, the size of the fractions may depend on the size of the errors such that the smaller the error, the smaller the fraction and the larger the error, the larger the fraction.

The invention also consists in a system comprising distortion counteracting equipment for ameliorating signal distortion in signal handling equipment and comprising adaption apparatus as described above for adapting the counteracting equipment.

The invention has been stated above in terms of methods of adapting distortion counteracting equipment; the invention extends also to programs for performing such methods. These programs could be held in a suitable data store such as a disk or memory.

In a preferred embodiment, the signal handling equipment is equipment for amplifying the input signal to create the output signal, comprising one or more amplifiers.

In the preferred embodiments, the distortion counteracting equipment is a lineariser. In a particularly preferred embodiment, the lineariser is a predistorter and the coefficients are for predistorting the input signal to the signal handling equipment. In another embodiment, the lineariser is a feed-forward lineariser in which the input signal is sensed, modified by the coefficients and combined with the amplifier output to give a linearising effect.

By way of example only, certain embodiments of the invention will now be described with reference to the accompanying figures, in which:

Figure 1 is a block diagram of a predistorter arrangement operating on an amplifier;

Figure 2 is a signal space diagram illustrating the discrepancy between ideal and actual output signals for the amplifier undergoing linearisation in Figure 1;

Figure 3 is a flowchart illustrating a routine for adapting a predistorter which operates according to a quadrature signal format; and

Figure 4 is a flowchart illustrating a routine for adapting a predistorter which operates according to an amplitude and phase signal format.

Figure 1 illustrates an arrangement for predistorting a radio frequency input signal RF_1 for an amplifier 10. The input signal RF_1 is predistorted in the digital domain using digital predistorter 12 to produce a digitally predistorted input signal S_3 for amplifier 10. A downconverter 14 reduces the frequency of the RF input signal RF_1 to a frequency supported by the sampling rate at which the predistorter 12 operates. The downconverted input signal is converted to the digital domain by analogue to digital converter (ADC) 16. The predistorted input signal S_3 is returned to the analogue domain by digital to analogue converter (DAC) 18 and upconverted to a desired frequency by upconverter 20 prior to being supplied as an input to amplifier 10.

The predistorter 12 can be adapted on the basis of feedback from the output RF_2 of amplifier 10. Discrepancies between the actual output RF_2 of amplifier 10 and its ideal output are used to adapt the predistortion of the amplifier input signal. The feedback signal is downconverted at downconverter 22 to a signal which is supported by the sampling rate of the digital aspect of the system, comprising predistorter 12 and control unit 24. The output of downconverter 22 is digitised by ADC 26 and supplied to control unit 24 as a feedback signal S_2. The control unit 24 uses the digitised feedback signal S_2 and the digitised input signal S_1 (from ADC 16) to adapt the predistortion.

If the original frequency of the input signal RF_1 is not incompatible with the sampling rate of predistorter 12, then downconverter 14 is not needed. If downconverter 14 is absent, then upconverter 20 is not required unless it is desired to shift the predistorted amplifier input signal to a frequency different from that of the original input signal RF_1. If the sampling rate of the digital aspect of the system supports the frequency of RF_2 then feedback downconverter 22 is not needed. The digitisation performed by ADCs 16 and 26 is performed in such a way as to preserve the amplitude and phase information in the signals being operated upon. For example, if the input to one of the ADCs is at baseband then the signal must be split into two paths with one path being in phase-quadrature to the second path with both paths then being digitised separately.

In this embodiment, the amplitude and phase of signal S_1 are modified in the predistorter 12 by the action of look-up tables (LUTs). This can be achieved by using a gain look-up

table L_G and a phase look-up table L_P, each indexed by a function f of the amplitude A_1 of signal S_1. Thus, when signal S_1 has amplitude A_1, value L_G (f(A_1)) is retrieved from look-up table L_G, value L_P (f(A_1)) is retrieved from look-up table L_P and these values are then used to predistort the signal S_1 according to the following equation:

$$S_3 = L_G(f(A_1)).S_1.e^{jL_P(f(A_1))}, \text{ where } S_1 = A_1.e^{ja}$$

Alternatively, predistorter 12 can contain an in-phase LUT L_I and a quadrature phase LUT L_Q. Again, these look-up tables are indexed by a function f of the amplitude A_1 of signal S_1 in order to provide values L_I (f(A_1)) and L_Q (f(A_1)), respectively. The retrieved LUT values are then used to predistort the input signal S_1 in quadrature format according to the following equation:

$$S_3 = L_I(f(A_1)).S_1 + j.L_Q(f(A_1)).S_1, where\, S_1 = A_1.e^{ja}$$

The function f of the input signal amplitude A_1 that is used to index the look-up tables can take any one of a large number of forms. The best form for f in any particular case is dependent on the characteristics of the modulation on the input signal RF_1. For example, the two most obvious forms are $f(A_1) = C.A_1$ and $f(A_1) = C.A_1^2$ where C is an arbitrary constant which can be 1.

To adapt the predistortion in response to errors in the output of amplifier 10, the control unit 24 compares the signals S_1 and S_2 to generate updated LUT values which are transferred to the LUTs in the predistorter 12. Prior to comparison, the signal vectors S_1 and S_2 are, within control unit 24, time aligned (for example by digitally delaying S_1) so as to remove any relative delay difference between them and phase aligned (for example by digitally adjusting the phase of S_1 or S_2) to eliminate any phase offset between them. These alignment processes enable an accurate comparison of S_1 and S_2 to allow the error between them and its relationship to the input signal amplitude A_1 to be determined independently of the modulation frequency.

The ideal or target output signal vector S_{2t} of amplifier 10 is defined as a linear function of the input, i.e. $S_{2t} = G.S_1$ where G is a constant. An error signal vector or error vector S_e is defined as the difference between the measured output signal vector and the target output signal vector, i.e. $S_e = S_2 - S_{2t}$. The error vector S_e is then described in terms of amplitude A_e and phase P_e components or in terms of two orthogonal vectors I_e and Q_e depending on whether the predistorter LUTs are in the amplitude and phase format or the quadrature format respectively. The relationship between the vectors S_2, S_{2t} and S_e is shown in the complex signal space diagram of Figure 2, which also illustrates the components A_e, P_e, I_e and Q_e of S_e (note that I_e and Q_e are not aligned with the I and Q axes of signal space but rather I_e is parallel to S_{2t}).

Thus, as time progresses, various values of S_e (in the appropriate one of the A_e, P_e and I_e, Q_e formats) are recorded. Since signal S_1 has a time varying amplitude A_1, the recorded error signals S_e are obtained for various input signal amplitudes A_1. The error signals S_e obtained are tabulated against bins or ranges of the function of the input signal amplitude $f(A_1)$ that is used to index the predistorter LUTs. Between predistorter updates, all error signals S_e falling within the same bin are accumulated and averaged to derive a mean error for that bin. Notionally therefore, the table created by tabulating the error signals S_e against $f(A_1)$ is a table of mean errors indexed by $f(A_1)$. The table of mean errors versus $f(A_1)$ can be filtered or curve-fitted to remove the effects of noise. The table of mean errors is then used to adjust the predistorter LUT values.

Where the predistorter operates amplitude and phase LUTs, each value in the LUTs is adjusted according to the appropriate one of the two following equations:

$$L_{G(n)}(f(A_1)) = L_{G(n-1)}(f(A_1)) - r.A_{e(n-1)}(f(A_1)).\frac{1}{A_1}$$

$$L_{P(n)}(f(A_1)) = L_{P(n-1)}(f(A_1)) - r.P_{e(n-1)}(f(A_1))$$

Alternatively, where the predistorter operates with in-phase and quadrature-phase LUTs, the look-up table values are adjusted using the following equations:

$$L_{I(n)}(f(A_1)) = L_{I(n-1)}(f(A_1)) - r.I_{e(n-1)}(f(A_1)).\frac{1}{A_1}$$

$$L_{Q(n)}(f(A_1)) = L_{Q(n-1)}(f(A_1)) - r.Q_{e(n-1)}(f(A_1)).\frac{1}{A_1}$$

In the four preceding equations, n-1 and n denote that the current LUT values (n-1) are used to produce the new LUT values (n).

The two pairs of equations above each describe a feedback control loop with the subtracted terms representing the feedback. The loop gain for each entry in the LUTs is defined as the ratio of the change in the feedback term to the change in the LUT value, i.e. $\frac{\Delta feedback\ term}{L_{x(n)}-L_{x(n-1)}}$ where x is G, P, I or Q as appropriate. In the case of each of the four feedback control loop equations above, it can be shown that the loop gain is approximately proportional to r and is independent of the input signal amplitude A_1 (provided that the effect of the amplifier non-linearity is ignored). The independence of the loop gain from A_1 is due to the term $\frac{1}{A_1}$ which appears in the feedback equations except that for $L_{P(n)}$. Using the above equations, the LUT values are updated for all values of the index $f(A_1)$. The revised LUT values can be filtered or curve-fitted to remove the effects of noise if desired.

The control unit 24 is able to vary the size of the loop gain by varying the size of r in response to the magnitude of the error vector S_e. If the distortion is judged to be high then the loop gain is made relatively large by setting r to a relatively large value so that the LUT values converge quickly to a solution which minimises the distortion in signal S_2. On the other hand, if the distortion in S_2 is low, then the LUT values are already approximately correct and a relatively small loop gain is selected by setting r to a relatively small value so that the effects of system noise and spurious signals on the shape of the look-up tables are minimised. The preferred method for setting r is to use a mathematical function to generate a number based on the mean error table information. For example, a sum of squares calculation may be performed on the mean errors in the table. A large result implies a large amount of distortion at the amplifier output and hence that a large loop gain is required to arrive at a solution for the LUT values. A small result implies that there is only a small amount of distortion in the output of the amplifier and hence that a small loop gain is required, giving slower convergence of the LUT values.

Figure 3 is a flowchart which further explains the process of updating predistorter LUT values in the case where in-phase and quadrature LUTs are used.

Figure 4 is a flowchart further explaining the process of updating predistorter values in the case where amplitude and phase LUTs are used.

In the embodiments described above, the predistorters are vector predistorters which are capable of reducing both AM (amplitude modulation) to AM distortion and AM to PM (phase modulation) distortion. It will be apparent to the skilled person that the predistorter could be a scalar predistorter which counteracts only either AM to AM or AM to PM distortion by providing only a gain or phase LUT respectively with the result that only gain or phase errors need to be tabulated for subsequently adjusting the LUT values.

CLAIMS

1. Apparatus for adapting distortion counteracting equipment, wherein said counteracting equipment employs a group of coefficients to adjust a consequential signal in order to ameliorate distortion in an output signal produced by signal handling equipment in response to an input signal, the apparatus comprising error measuring means for measuring errors in the output signal, modifying means for modifying at least some measured errors to render them less dependent on the input signal's amplitude and correcting means for changing coefficients by amounts dependent on modified errors.

2. Apparatus according to claim 1, wherein the coefficients are indexed by a function of the input signal amplitude to allow the appropriate coefficient or coefficients to be selected to partake in the amelioration of the distortion in the signal handling equipment's output signal.

3. Apparatus according to claim 2, wherein the measuring means determines measured errors for values or ranges of the function.

4. Apparatus according to claim 3, wherein the modifying means modifies a measured error by operating on the measured error with the input signal amplitude value corresponding to the function value indexing the error.

5. Apparatus according to claim 4, wherein the modifying means modifies a measured error by dividing the measured error by the input signal amplitude value corresponding to the function value indexing the measured error.

6. Apparatus according to claim 3, 4 or 5, wherein the correcting means corrects a coefficient using a modified error indexed by the same value of the function.

7. Apparatus according to claim 6, wherein the correcting means corrects a coefficient by subtracting from a coefficient a fraction of the modified error indexed by the same value of the function.

8. Apparatus according to claim 7, wherein the fraction is adjustable.

9. Apparatus according to any preceding claim, wherein the measuring means calculates each measured error from a group of measured error values.

10. Apparatus according to any preceding claim, wherein the distortion counteracting equipment is a predistorter operating on the signal handling equipment.

11. Apparatus according to any preceding claim, wherein the signal handling equipment comprises signal amplifying means.

12. A system comprising distortion counteracting equipment for ameliorating signal distortion in signal handling equipment and apparatus for adapting distortion counteracting equipment as claimed in any preceding claim.

13. A method of adapting distortion counteracting equipment, wherein said counteracting equipment employs a group coefficients to adjust a consequential signal in order to ameliorate distortion in an output signal produced by signal handling equipment in response to an input signal, the method comprising measuring errors in the output signal, modifying at least some measured errors to render them less dependent upon the input signal's amplitude and changing coefficients by amounts dependent upon modified errors.

14. A method according to claim 13, wherein the coefficients are indexed by a function of the input signal amplitude to allow the appropriate coefficient or coefficients to be selected to partake in the amelioration of distortion in the signal handling equipment's output signal.

15. A method according to claim 14, wherein the measured errors are determined for values or ranges of the function.

16. A method according to claim 15, wherein a measured error is modified by operating on the measured error with the input signal amplitude value corresponding to the function value indexing the error.

17. A method according to claim 16, wherein a measured error is modified by dividing the measured error by the input signal amplitude value corresponding to the function value indexing the measured error.

18. A method according to claim 15, 16 or 17, wherein a coefficient is corrected using a modified error indexed by the same value of the function.

19. A method according to claim 18, wherein a coefficient is corrected by subtracting from it a fraction of the modified error indexed by the same value of the function.

20. A method according to claim 19, wherein the fraction is adjustable.

21. A method according to any one of claims 13 to 20, wherein each measured error is calculated from a group of measured error values.

22. A method according to any one of claims 13 to 21, wherein the distortion counteracting equipment is a predistorter operating on the signal handling equipment.

23. A method according to any one of claims 13 to 22, wherein the signal handling equipment comprises signal amplifying means.

24. A programme for causing data processing equipment to perform the method of any one claims 13 to 23.

25. Apparatus for adapting distortion counteracting equipment, substantially as hereinbefore described with reference to Figures 1, 2 and 3 or Figures 1, 2 and 4.

26. A method of adapting distortion counteracting equipment, substantially as hereinbefore described with reference to Figures 1, 2 and 3 or Figures 1, 2 and 4.

The Patent Office

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Application No: GB 0114804.8 **Examiner:** Keith Sylvan
Claims searched: 1-26 **Date of search:** 13 February 2002

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.T): H3W (WULPR)

Int Cl (Ed.7): H03F (1/32)

Other:

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
X	EP1011192 A2	Nortel. See paragraphs 32-35.	1,2,10-14,22,23 at least
X	WO99/05869 A2	Harris. See page 13 lines 11-14, especially "normalized" at line 12.	1,13 at least
A	EP0731556 A1	NEC. See equations 9-12.	-
A	WO98/12800 A1	Spectrian. See divider 90 in figure 1.	-

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
		E	Patent document published on or after, but with priority date earlier than, the filing date of this application.
&	Member of the same patent family		